Multi-messenger astronomy:

The key to high energy (astro)physics with neutrinos

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High energy ν's: A new window

MeV ν detectors:

- Solar & SN1987A ν's
- Stellar physics (Sun's core, SNe core collapse)
- ν physics

>0.1 TeV ν detectors:

- Extend ν horizon to extra-Galactic scale

  [MeV ν detectors limited to local (Galactic) sources

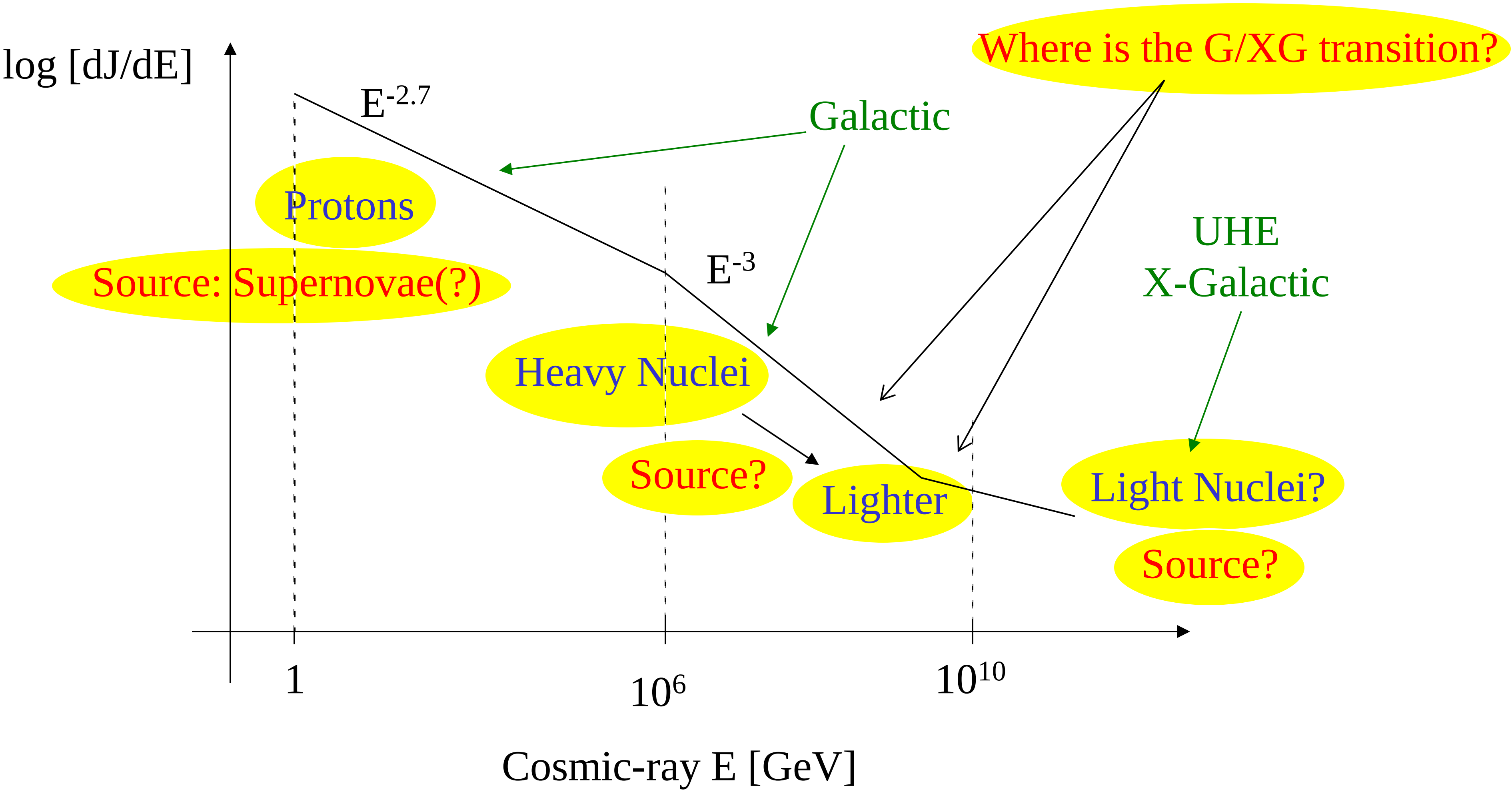
  10kt @ 1MeV→1Gton @ TeV , $\sigma_{TeV}/\sigma_{MeV} \sim 10^6$]
- Study "Cosmic accelerators": pγ, pp → π's → ν's
- ν physics

Cosmic accelerators:

- Open questions → Prime scientific motivation
- Observed properties → Detector characteristics

CRs and their sources:
Open Questions

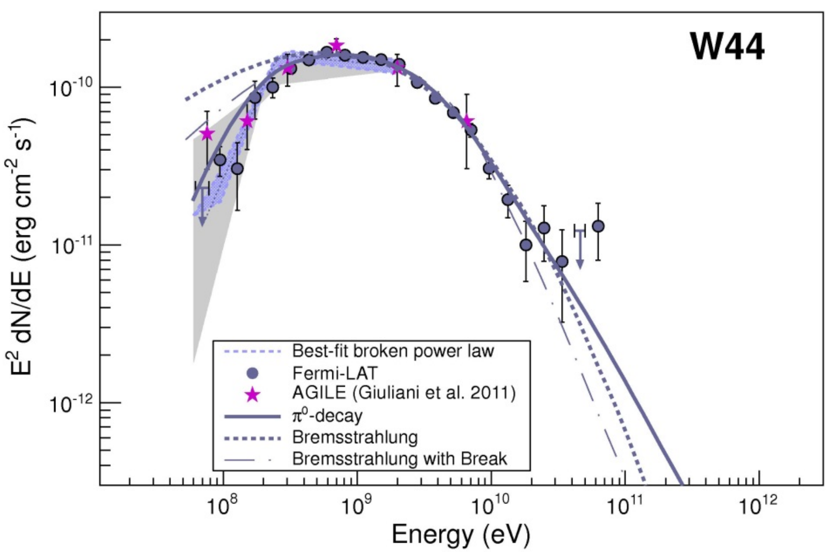
Open Qs: I. The origin of CRs

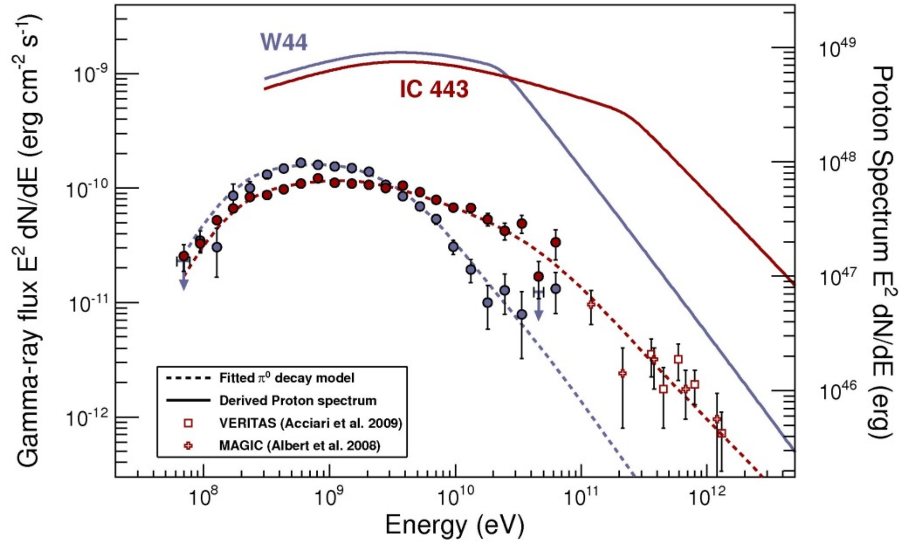


Are SNRs the low E CR sources?

- So far, no clear evidence.
  Electromagnetic observations- ambiguous.

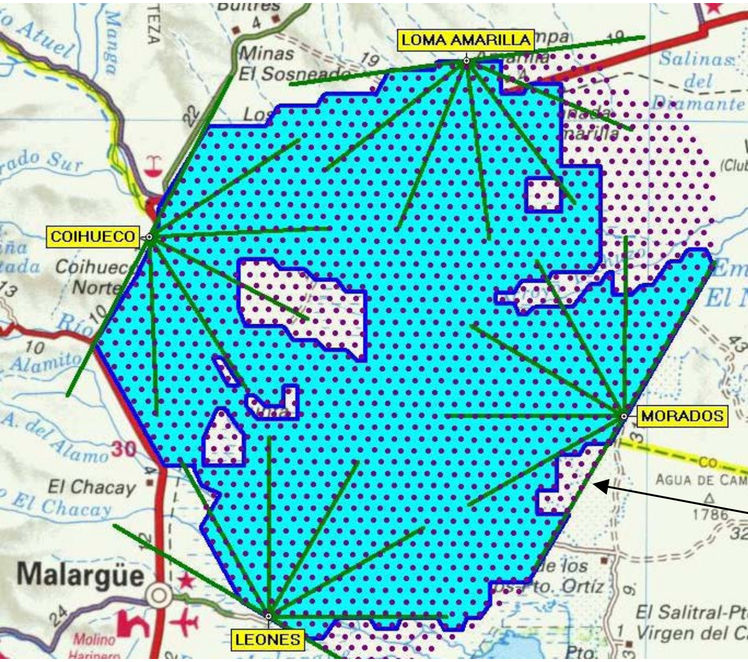
E.g.: "π decay signature" [Ackermann et al. 13]:





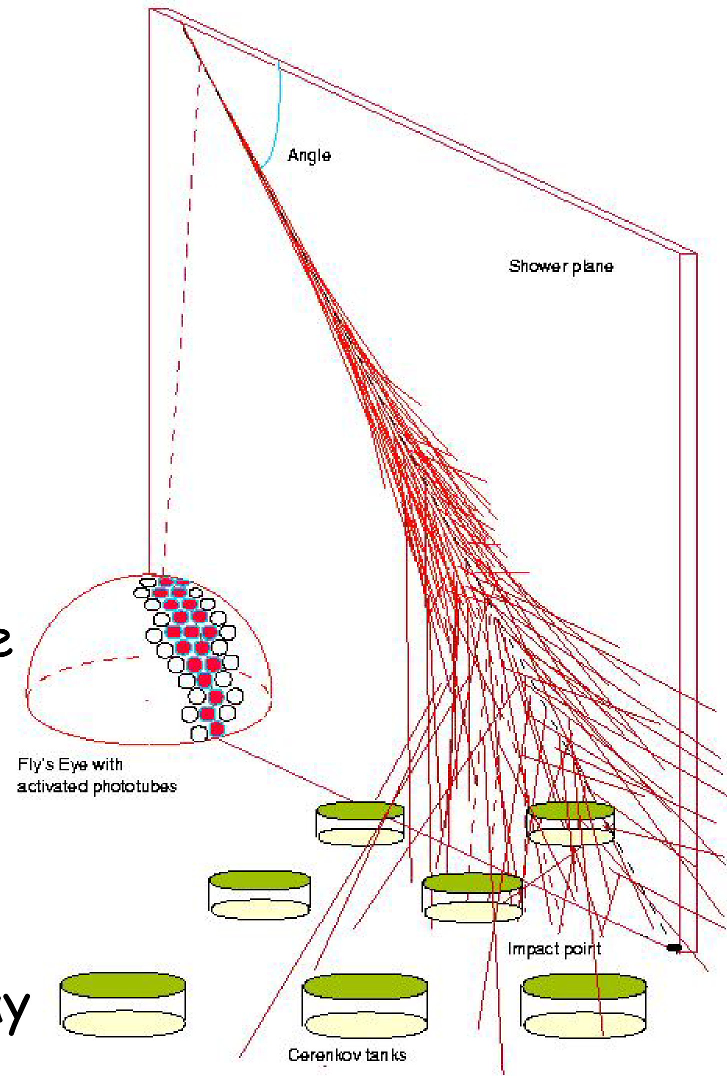
UHE, $>10^{10}$GeV, CRs

$J(>10^{11}\text{GeV}) \sim 1$ / 100 km^2 year 2π sr



Auger:
3000 km^2

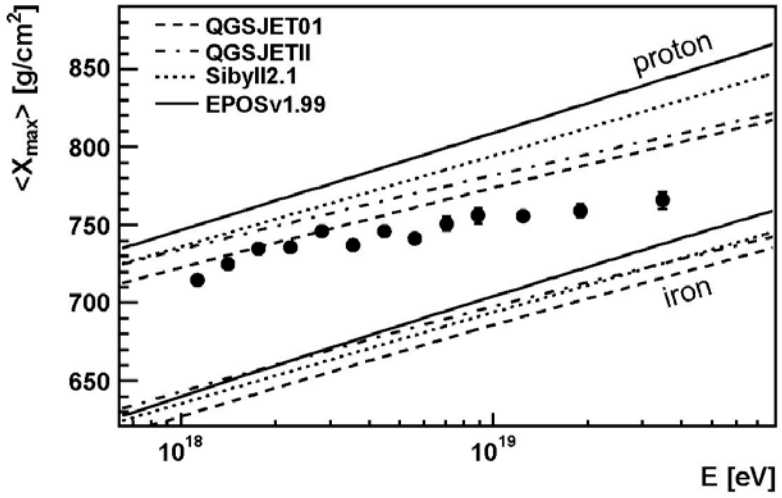
Fluorescence detector

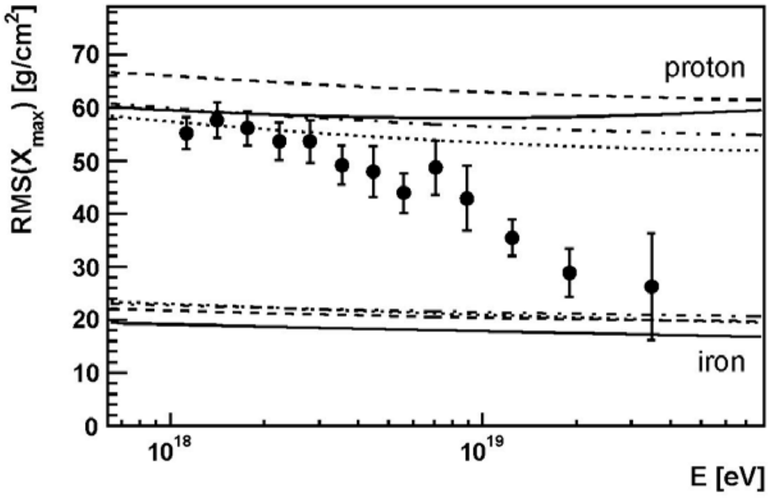


Ground array

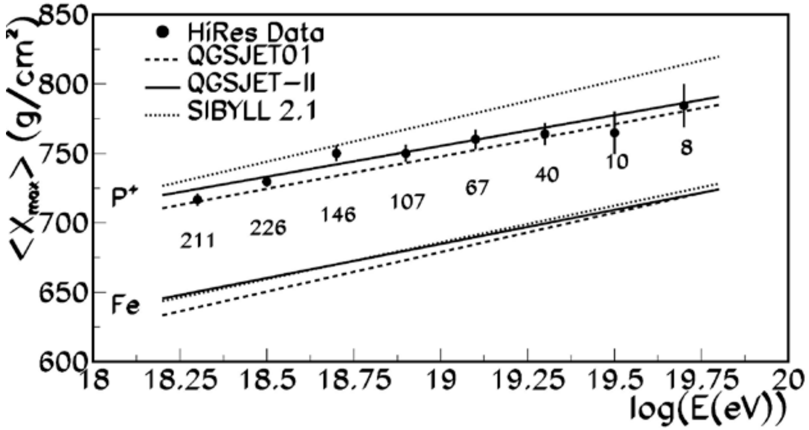
Open Qs: II. UHE Composition

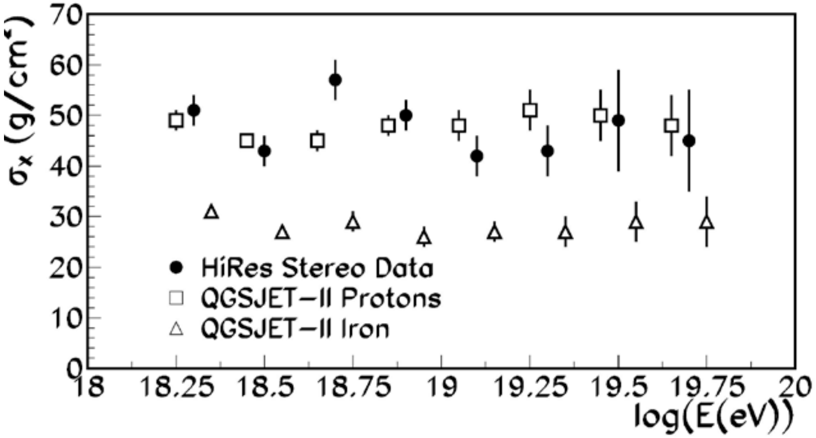
Auger 2010





HiRes 2010 (& TA 2011)

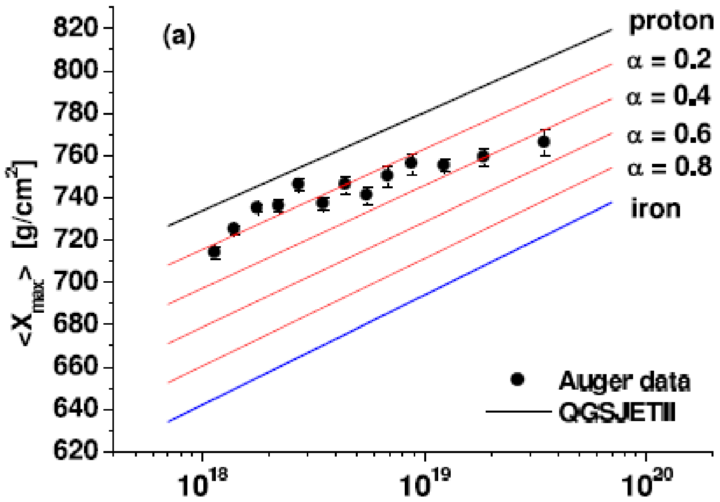


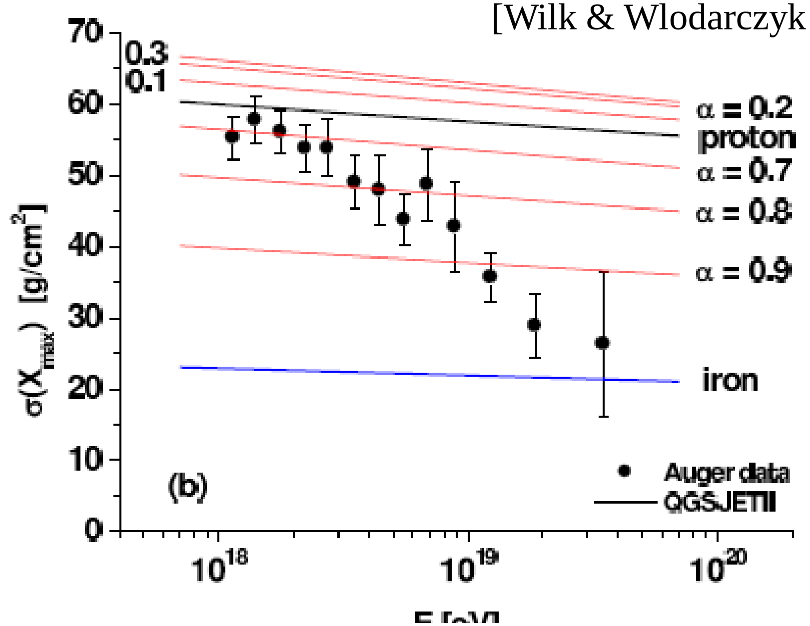


Open Qs: II. UHE Composition

Auger 2010

[Wilk & Wlodarczyk 10]*





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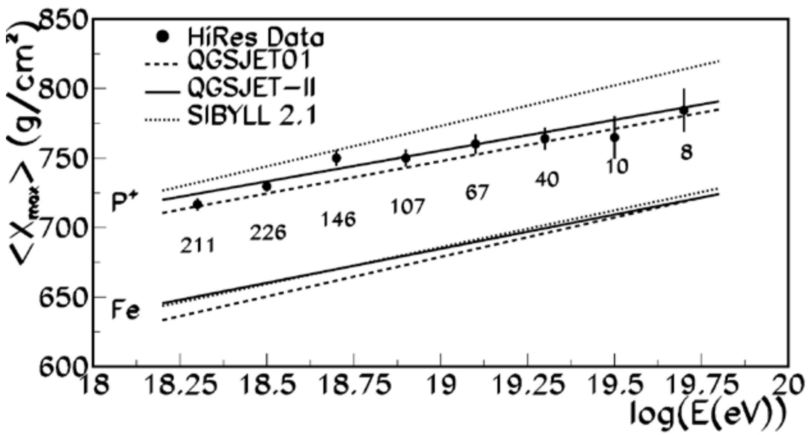
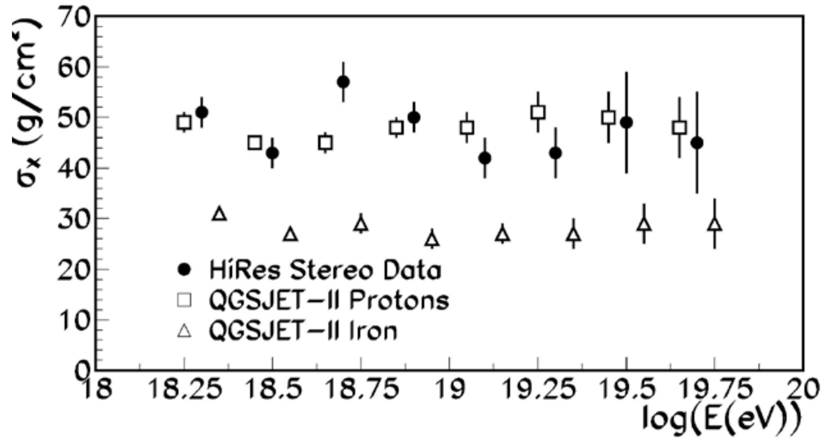
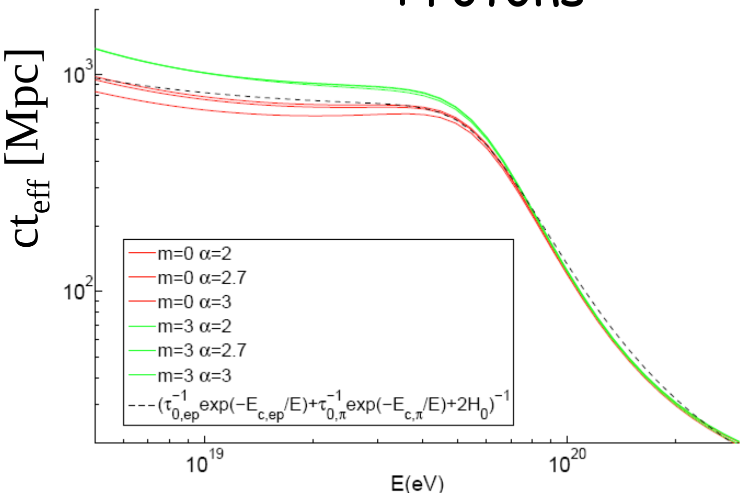


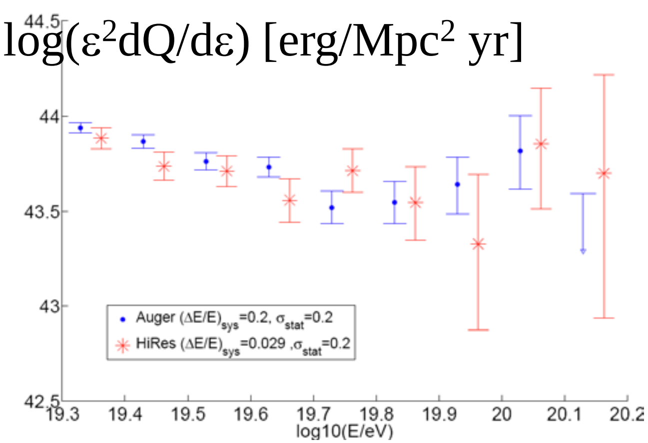


[*Possible acceptable solution?, Auger collaboration 13]

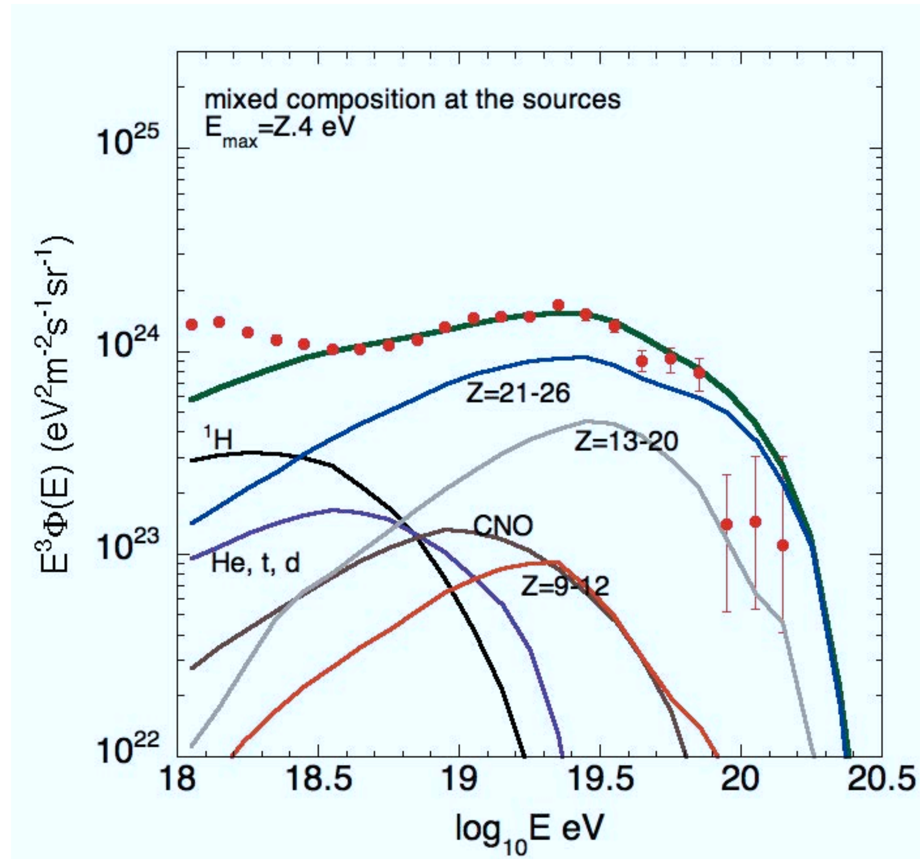
UHE: Energy production rate & spectrum

Protons





Mixed composition



[Allard 12]

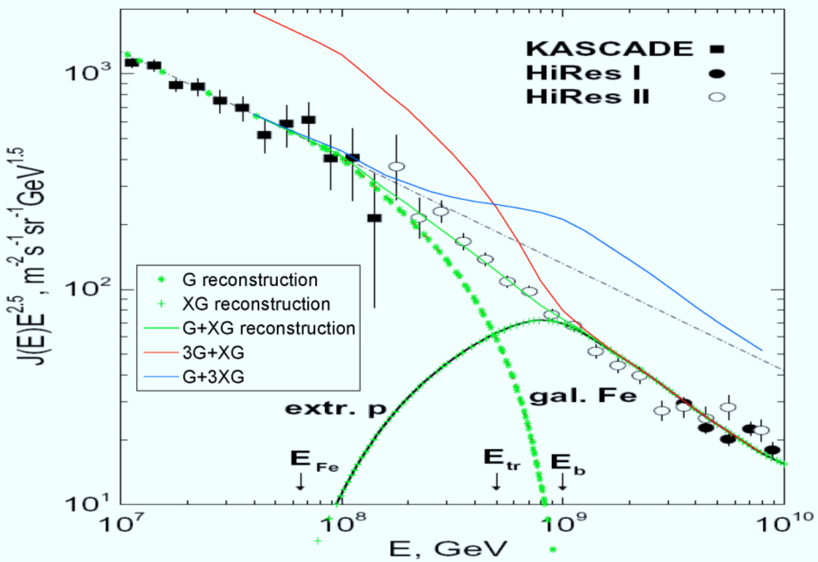
$\varepsilon^2(dQ/d\varepsilon)$ =Const.

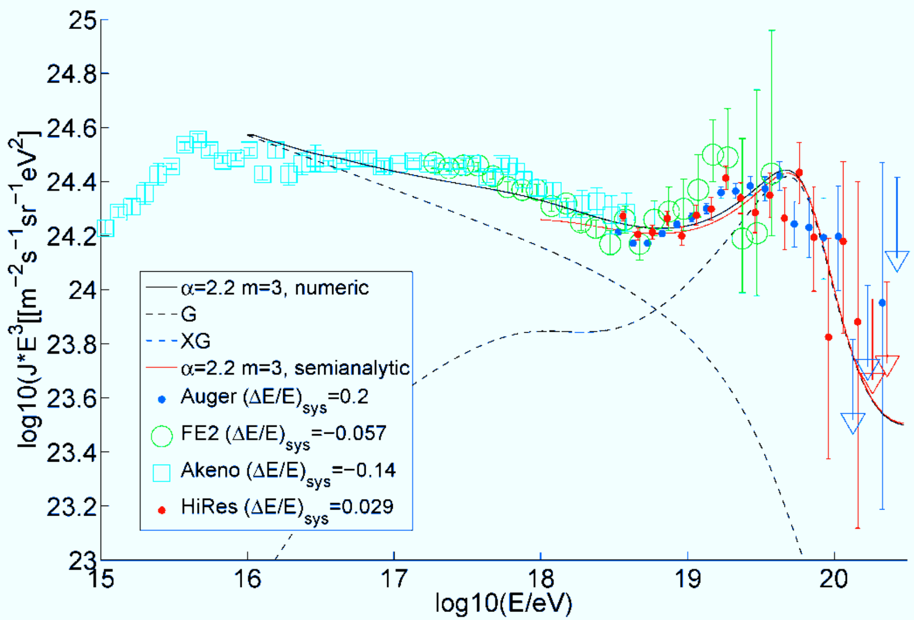
= 0.5(+-0.2) x 10^{44} erg/Mpc^3 yr + GZK

[Katz & EW 09]

Open Qs: III. Where is the G-XG transition?

@ E<10^{18}eV ? $\quad\quad$ $\varepsilon^2(dQ/d\varepsilon)$ =Const → @ E~10^{19}eV





[Katz & EW 09]

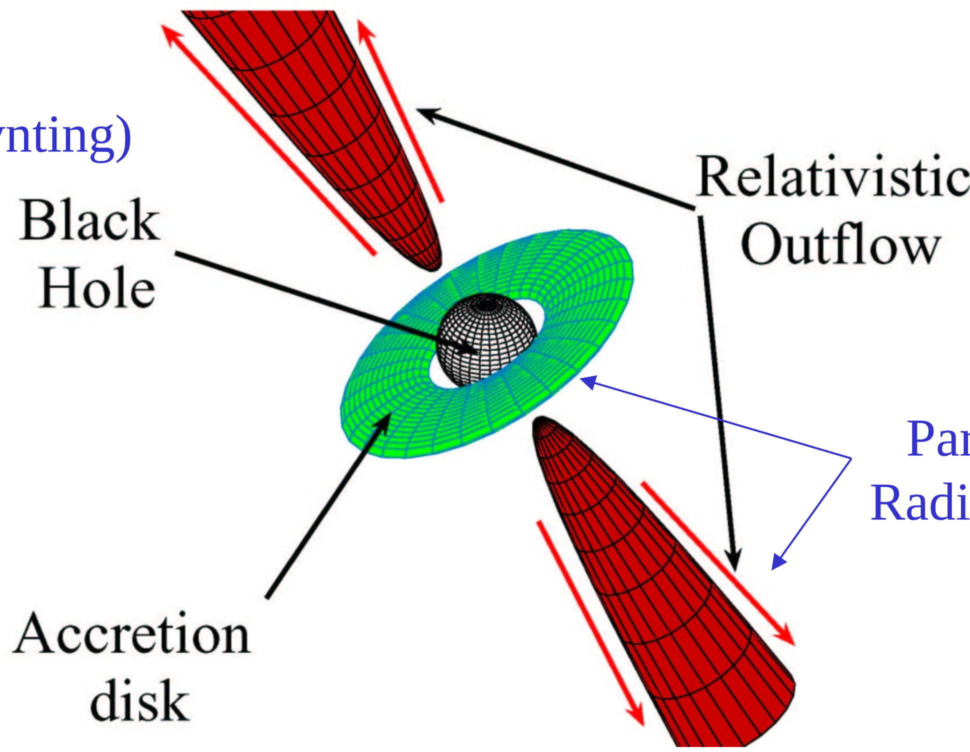
- Fine tuning
- Inconsistent with Fermi's XG γ (<1TeV) flux

[Gelmini 11]

Open Qs: IV. Source physics challenges

- Electromagnetic acceleration in astrophysical sources requires
  $L > L_B > 10^{14} L_{Sun} (\Gamma^2/\beta) (\varepsilon/Z\ 10^{20} eV)^2$ erg/s [Lovelace 76; EW 95, 04; Norman et al. 95]
- GRB: $10^{19} L_{Sun}$, $M_{BH} \sim 1 M_{sun}$, $\dot{M} \sim 1 M_{sun}/s$, $\Gamma \sim 10^{2.5}$
  AGN: $10^{14} L_{Sun}$, $M_{BH} \sim 10^9 M_{sun}$, $\dot{M} \sim 1 M_{sun}/yr$, $\Gamma \sim 10^1$
- No steady sources at $d < d_{GZK}$ → Transient Sources (AGN flares?)

Energy extraction;
Jet acceleration and
content (kinetic/Poynting)

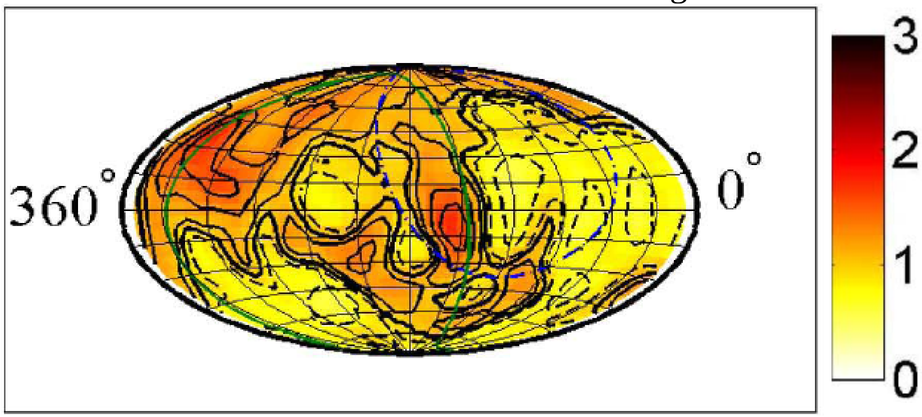


Particle acceleration,
Radiation mechanisms

UHE: Do we learn from (an)isotropy?

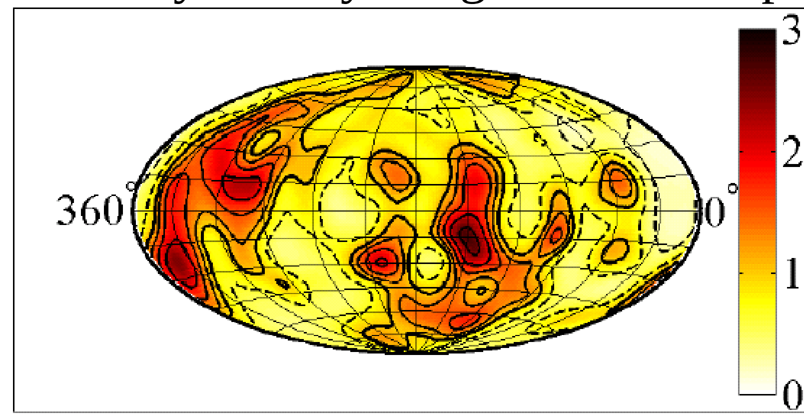
E>60EeV

CR intensity map ($\rho_{source} \sim \rho_{gal}$)



[Kashti & EW 08]

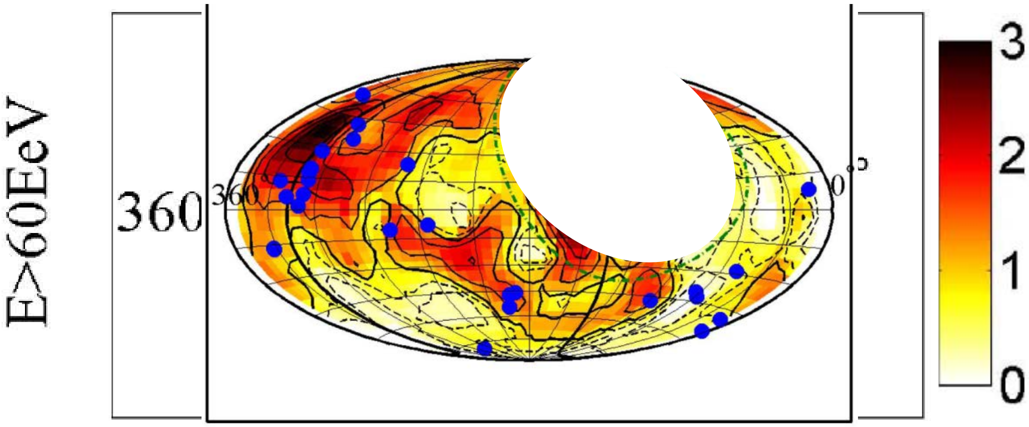
Galaxy density integrated to 75Mpc



[EW, Fisher & Piran 97]

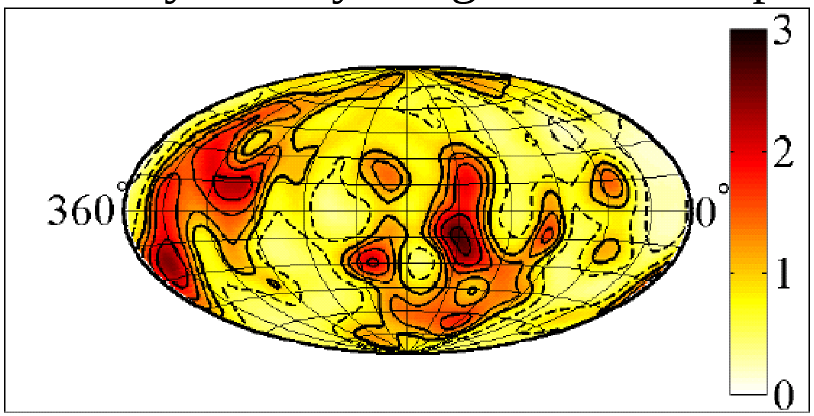
UHE: Do we learn from (an)isotropy?

Biased ($\rho_{source} \sim \rho_{gal}$ for $\rho_{gal} > \overline{\rho_{gal}}$)



[Kashti & EW 08]

Galaxy density integrated to 75Mpc



[EW, Fisher & Piran 97]

- Anisotropy @ 98% CL; Consistent with LSS

[Kotera & Lemoine 08; Abraham et al. 08… Oikonomou et al. 13]

- Anisotropy of Z at $10^{19.7}$eV implies

  Stronger aniso. signal (due to p) at $(10^{19.7}/Z)$ eV

  Not observed → No high Z at $10^{19.7}$eV

[Lemoine & EW 09]

UHECR experiments: prospects?

- Unlikely to identify the sources.
- Composition?

ν astronomy to the rescue

HE ν: UHECR bound

- $p + \gamma \rightarrow N + \pi$
  $\pi^0 \rightarrow 2\gamma$; $\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$

→ Identify UHECR sources
  Study BH accretion/acceleration physics

- For all known sources, $\tau_{\gamma p} <= 1$:

$$\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu} \le \Phi_{\rm WB} \equiv 10^{-8}\,\zeta \left(\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\,\mathrm{erg/Mpc^3 yr}} \right) \frac{\mathrm{GeV}}{\mathrm{cm^2 s\ sr}}$$

[EW & Bahcall 99; Bahcall & EW 01]

$$\zeta = 1, 5 \quad \text{for} \quad f(z) = 1, (1+z)^3$$

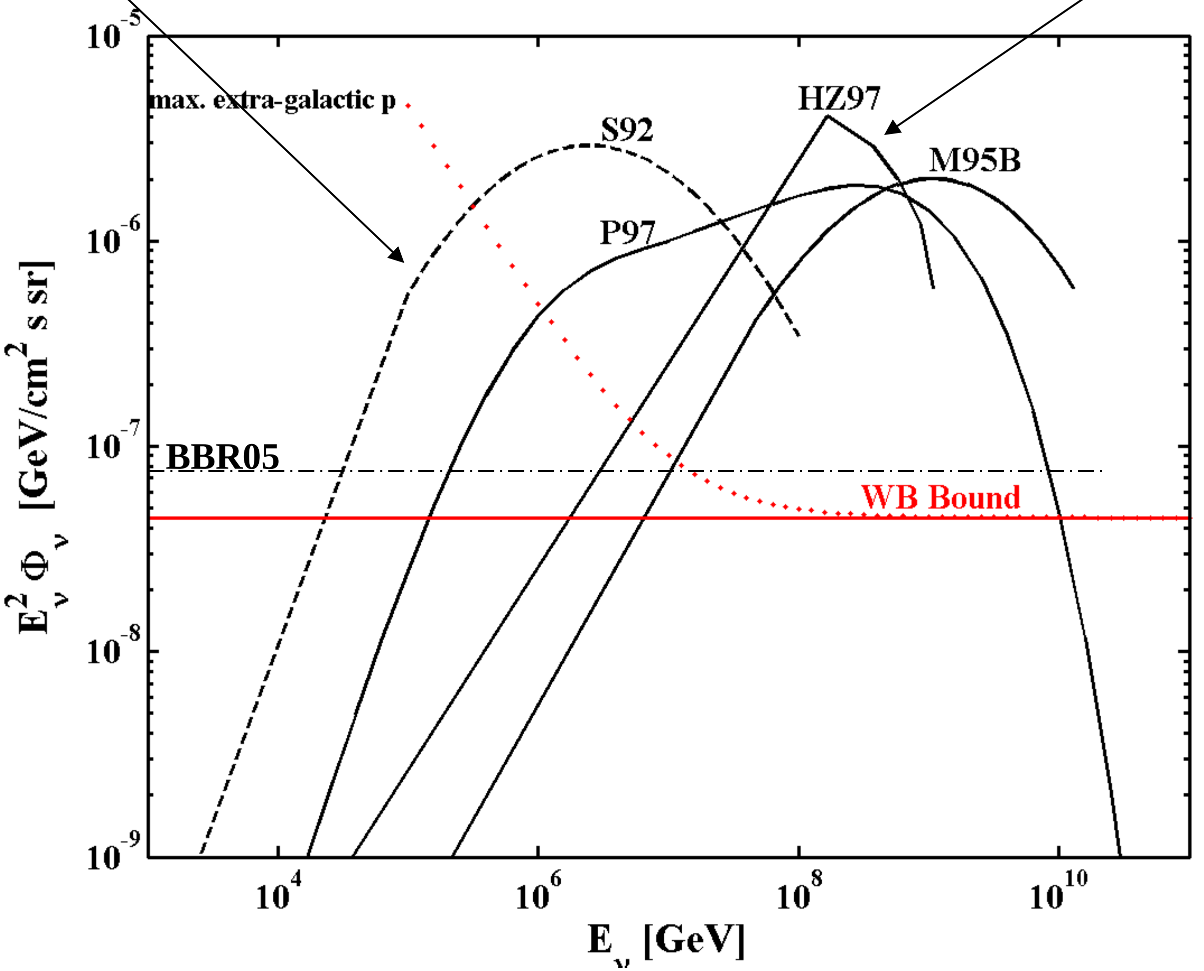
- If X-G p's: $\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu}(10^{19}\,\mathrm{eV}) = \Phi_{\rm WB}$

[Berezinsky & Zatsepin 69]

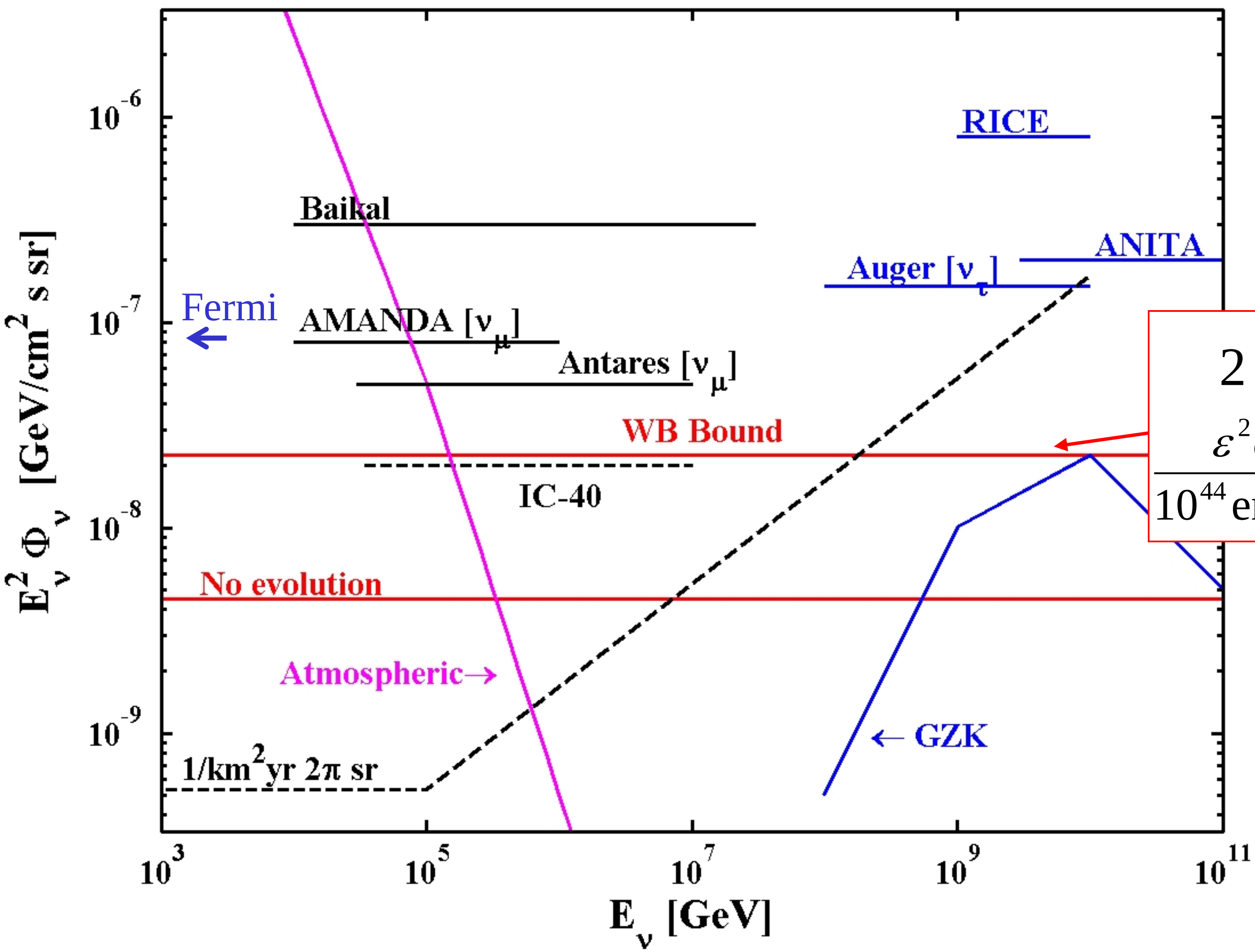
→ Identify primaries, determine f(z)

“Hidden” (ν only) sources

Violating UHECR bound



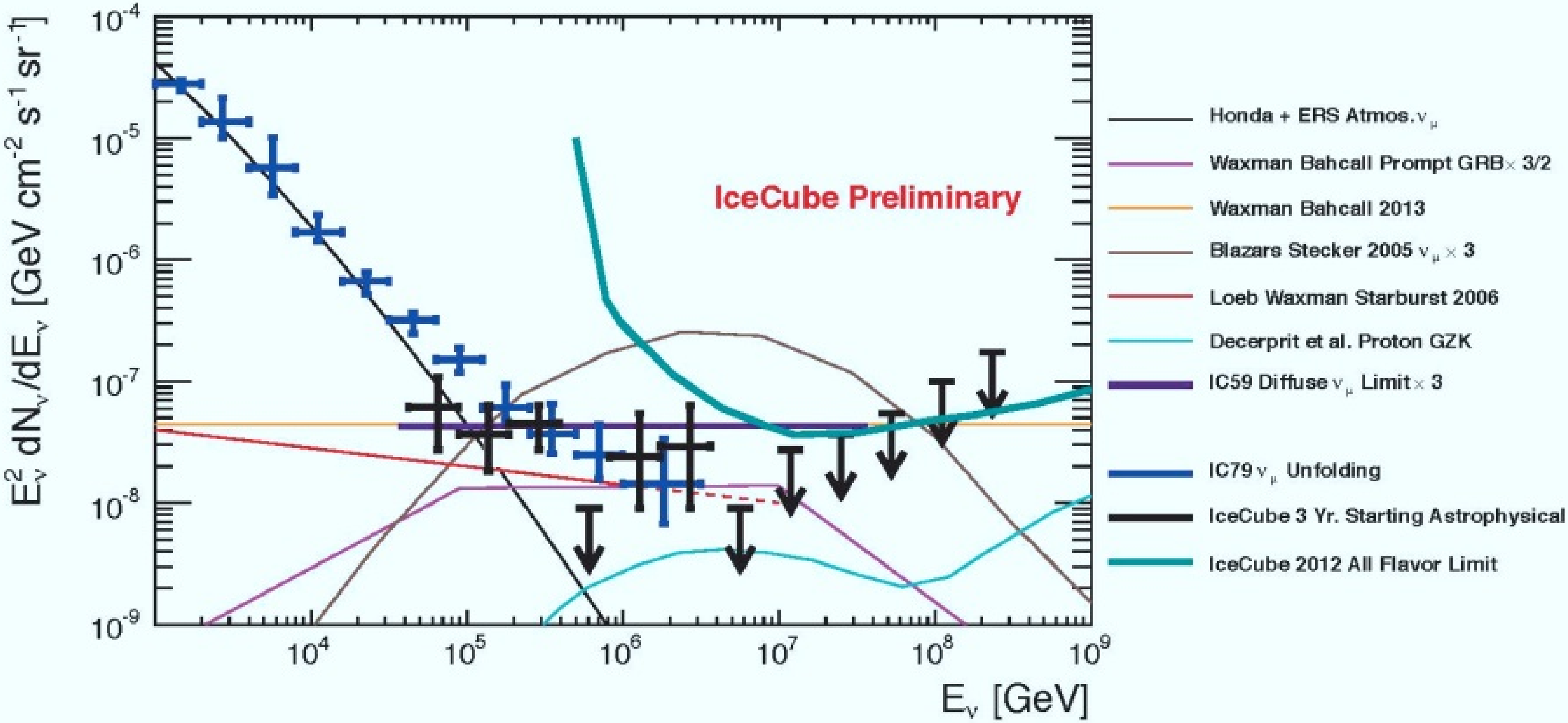
Bound implications: ν experiments



2 flavors,

$$\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\,\mathrm{erg/Mpc^3 yr}} = 0.5$$

Context



Consistent with Isotropy and
with $\nu_e:\nu_\mu:\nu_\tau=1:1:1$ (π deacy + cosmological prop.).

IceCube's detection: Implications

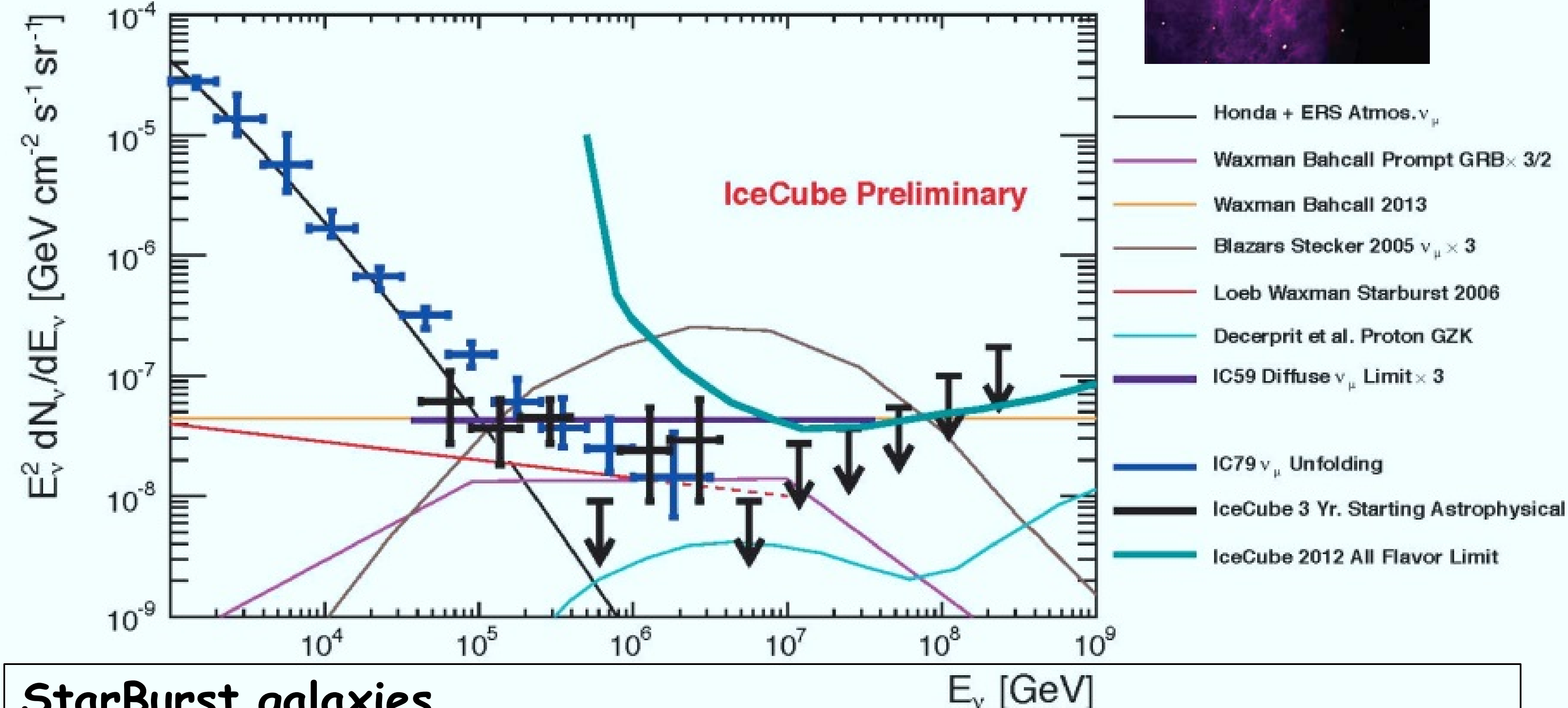
- Unlikely Galactic: $\varepsilon^2\Phi_\gamma \sim 10^{-7}(E_{0.1TeV})^{-0.7}$GeV/cm^{2}s sr [Fermi]
  $\rightarrow \varepsilon^2\Phi_\nu \sim 10^{-9}(E_{0.1PeV})^{-0.7}$GeV/cm^{2}s sr $\ll \Phi_{WB}$

- DM decay?
  The coincidence of 50TeV<E<2PeV ν flux, spectrum (& flavor) with the WB bound is unlikely a chance coincidence.

- XG distribution of sources,
  $\varepsilon^2(dQ/d\varepsilon)_{PeV-EeV} \sim \varepsilon^2(dQ/d\varepsilon)_{>10EeV}$, $\tau_{\gamma p(pp)} >\sim 1$ ["Calorimeters"]
  Or:
  $\varepsilon^2(dQ/d\varepsilon)_{PeV-EeV} \gg \varepsilon^2(dQ/d\varepsilon)_{>10EeV}$, $\tau_{\gamma p(pp)} \ll 1$
  & Coincidence over a wide energy range.

- $\varepsilon^2(dQ/d\varepsilon) \sim \varepsilon^0$ implies: p, G-XG transition at $\sim 10^{19}$eV.

Context



<u>StarBurst galaxies</u>

Radio, IR & γ-ray (GeV-TeV) observations →

Starbursts are calorimeters for E/Z reaching at least 10PeV;

Were predicted to produce the observed ν signal.

π production: p/A—p/γ

- π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (propagation)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1

- p(A)-p: $\varepsilon_\nu/\varepsilon_p$~1/(2x3x4)~0.04 ($\varepsilon_p$→$\varepsilon_A$/A);
  - IR photo dissociation of A does not modify Γ;
  - Comparable particle/anti-particle content.

- p(A)-γ: $\varepsilon_\nu/\varepsilon_p$~ (0.1—0.5)x(1/4)~0.05;
  - Requires intense radiation at ε_γ>A keV;
  - Comparable particle/anti-particle content,
    ν_e excess if dominated by Δ resonance (dlog n_γ/dlog ε_γ<-1).

[Spector, EW & Loeb 14]

Some comments RE next steps

- The most natural explanation of

  Isotropic, ν_e:ν_μ:ν_τ=1:1:1, ϕ~ϕ_{WB} at @ TeV—2PeV

Is: - UHE CRs are p's, produced by

- XG sources with $\varepsilon^2(dQ/d\varepsilon)$~const. from ~PeV to >10EeV,
- residing in "calorimeters" (starbursts?).
- G/XG transition @ ~10EeV.

  (π^0 γ's cascade to <0.1TeV, consistent w/Fermi's limit).

- The number of events provided by IceCube

  (~1/yr @ E>1 PeV, ~10/yr @ E>0.1PeV)

  will not be sufficient for an accurate determination of spectrum, flavor ratio and (an)isotropy.

- An (independent) confirmation of

  {XG p @ UHE, G/XG transition @ 10 EeV}

  will be provided by the detection of GZK ν's.

The key next step: EM source identification

- Identify >10PeV CR sources;
  ν & EM observations will enable us to
  resolve key open Qs in the accelerators' physics
  (BH jets, particle acceleration, collisionless shocks…),
  determine UHECR source identity.

- Fundamental/ν physics
  - π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (Osc.)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1
    → τ appearance [Learned & Pakvasa 95; EW & Bahcall 97]
  - GRBs: ν-γ timing (10s over Hubble distance)
    → LI to $1:10^{16}$; WEP to $1:10^{6}$ a [EW & Bahcall 97; Amelino-Camelia,et al.98; Coleman &.Glashow 99; Jacob & Piran 07]
  * Understanding the source w/ EM crucial
    (e.g. strong B may lead to $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:2 @ high E [Kashti & EW 05])

- Optimistic (>100's of ν's with flavor identification):
  Constrain flavor mixing, new phys. [Blum, Nir & EW 05; Winter 10; Pakvasa 10]

Identifying the sources

- The angular resolution of ν-"telescopes", ~1deg or worse, will not allow one to identify cosmologically distributed sources;
  Multiple events will constrain L_ν (but will not identify).

- Steady UHECR sources are unlikely detectable:
  $A_{effective}(10^{14}eV\ \nu \sim 10^{-4}km^2) \sim 10^{-7.5}\ A_{effective}(10^{19}eV\ CR \sim 10^{3.5}km^2)$
  → Not detectable in ν's unless $L_\nu >> 100 L_{CR}$, which
  Cannot be the case since $Q_{CR} \sim Q_\nu$.

- The only hope is to associate a ν with an EM transient.
  Luckily, UHECR sources must be bright transients.
  Required: Wide field EM monitoring, and
  Real time alerts for follow-up of high E ν events.

- Note: Φ_ν(source) may be << Φ_ν(calorimeter)~Φ_{WB} [Φ_ν(GRB) ~0.1 Φ_{WB}],
  P(nearby source for efficient follow up)~$A^{3/2}$.

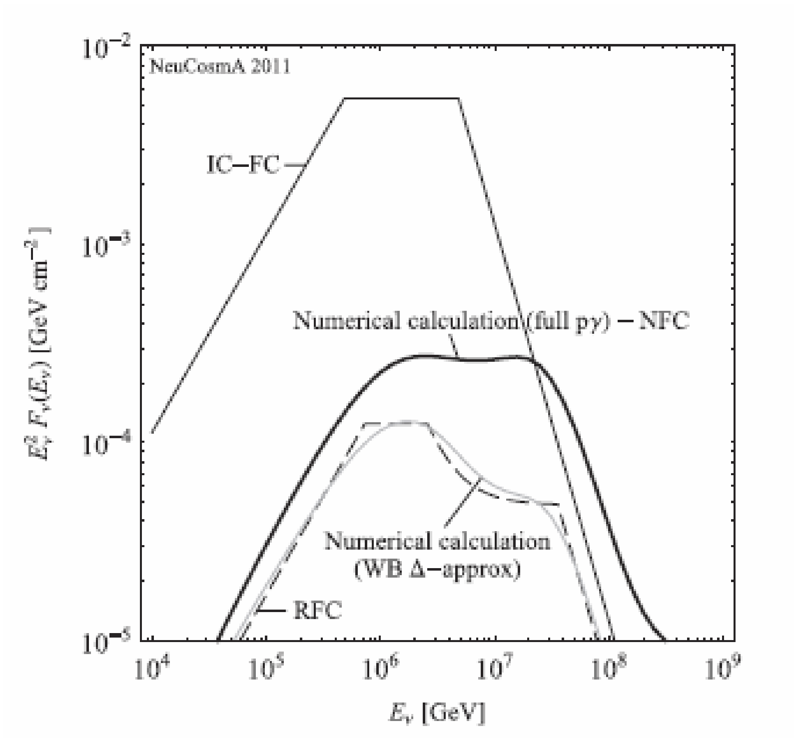
IceCube's GRB limits

- No ν's associated with ~200 GRBs (~2 expected).
- IC analyses overestimate GRB flux predictions, and ignore model uncertainties.
- IC is achieving relevant sensitivity.

$$\varepsilon_{\nu,b} = 500\left(\frac{\varepsilon_{\gamma,b}}{1\text{MeV}}\right)^{-1}\Gamma_{2.5}^{2}\,\text{TeV} \approx 1\text{PeV}$$

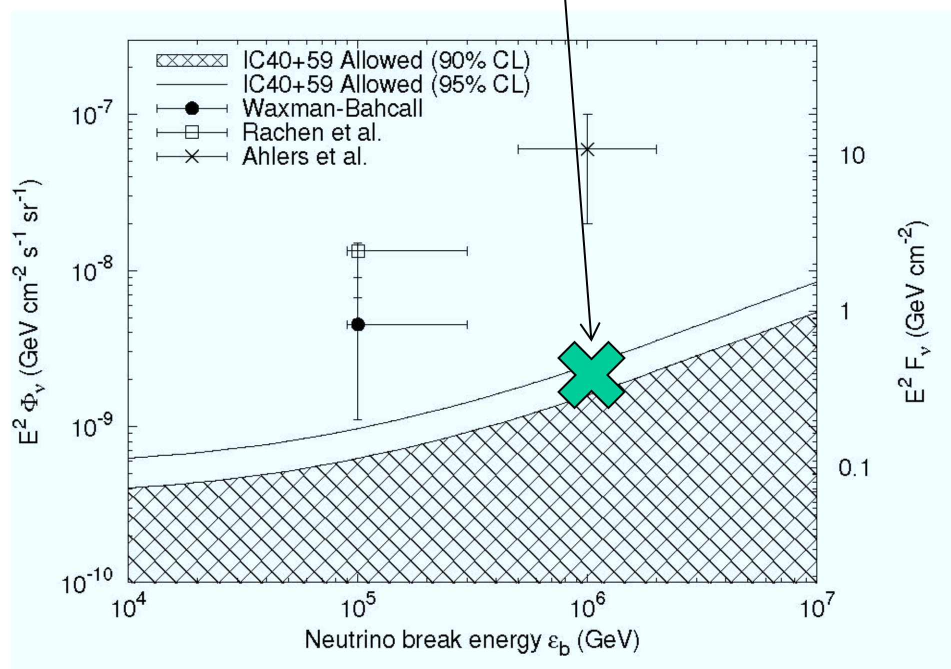
$$\Phi_{\text{GRB}} \approx 0.2\Phi_{\text{WB}}$$

[EW & Bahcall 97]

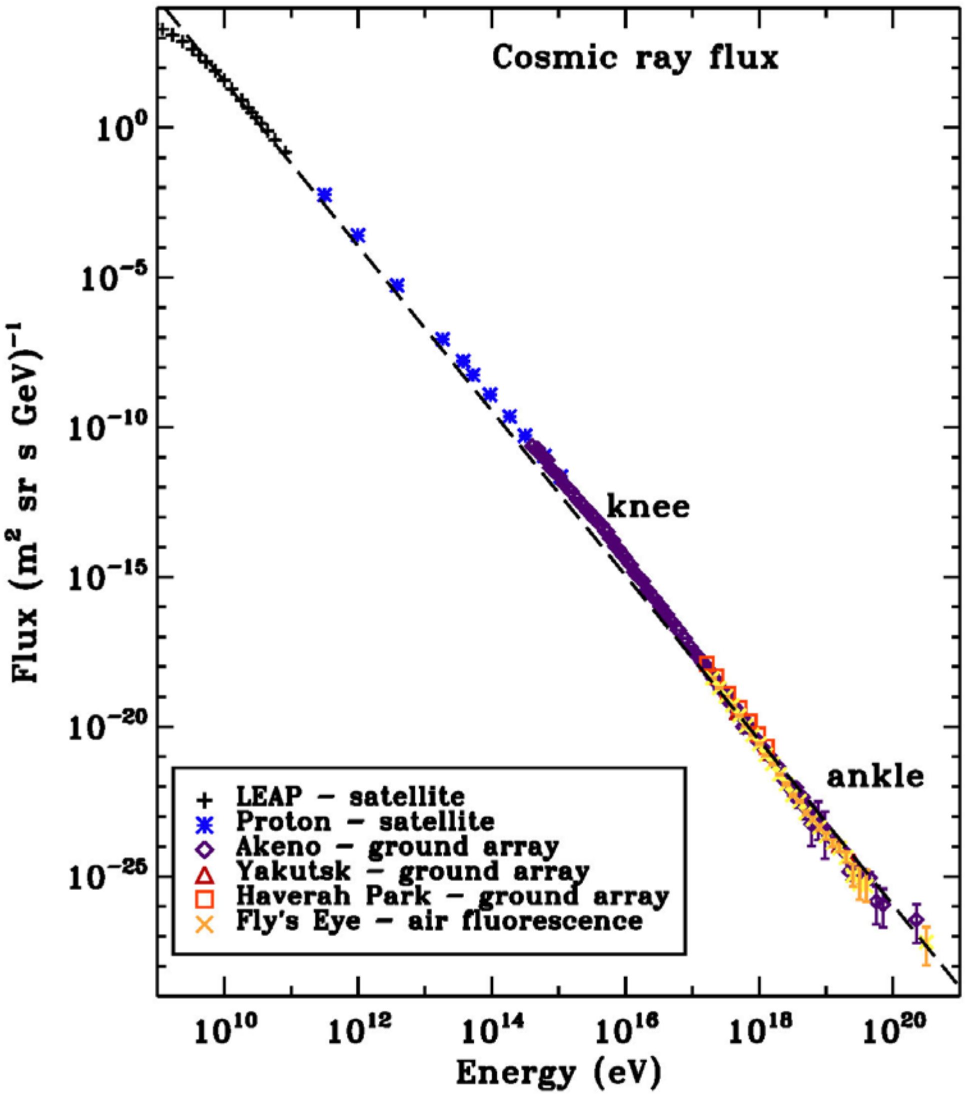


[Hummer, Baerwald, and Winter 12;

see also Li 12; He et al 12]

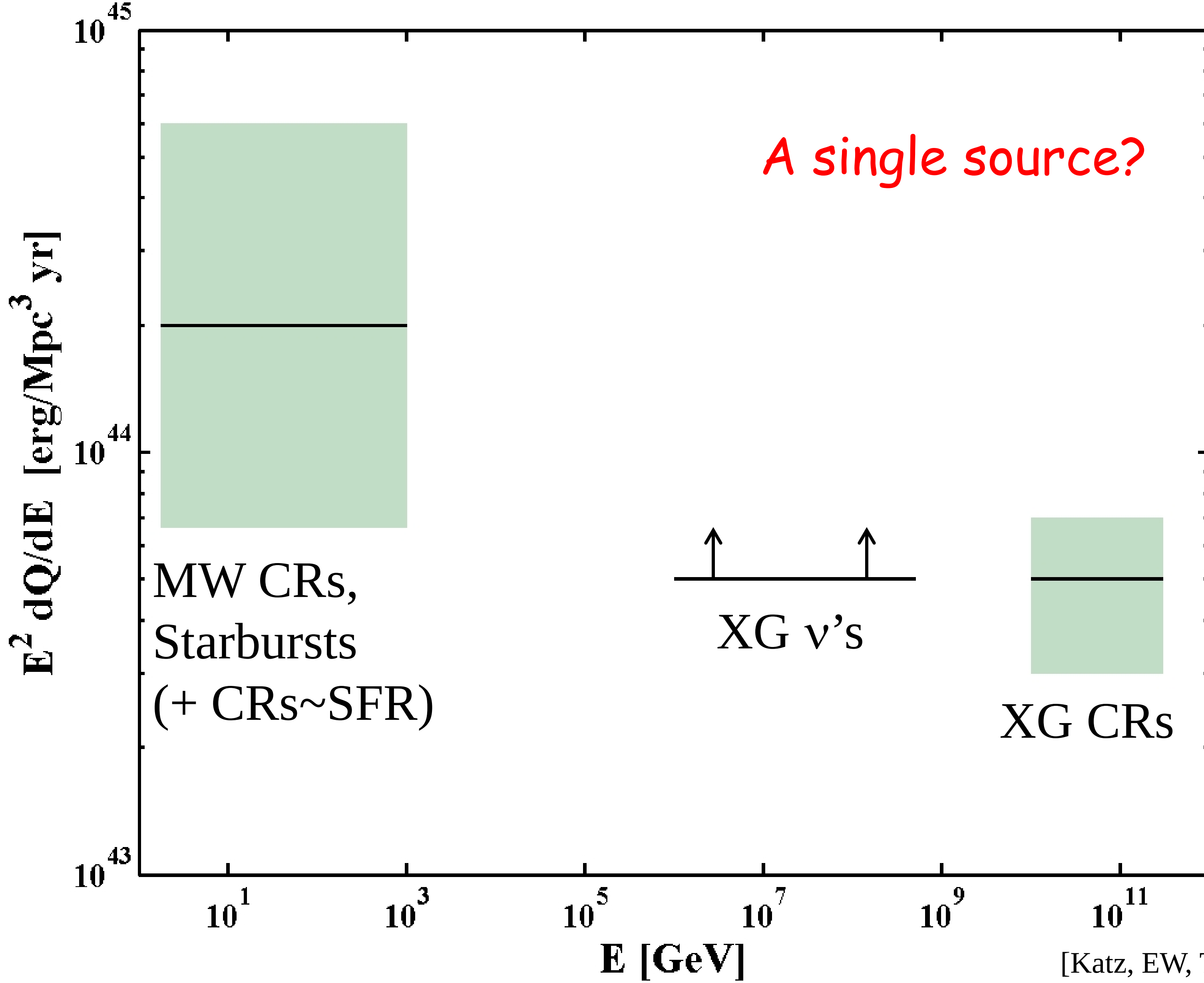


The cosmic ray spectrum



[From Helder et al., SSR 12]

The cosmic ray generation spectrum



[Katz, EW, Thompson & Loeb 14]

What is required for the next stage of the ν astronomy revolution

- Significantly (x10) larger effective A/V @ E>~0.1 PeV
  → Accurate spectrum, flavor content, (an)isotropy .

- Adequate sensitivity for detecting the ~10EeV GZK ν's.

- EM association- Bright transients are the prime targets.
  Via: Wide field EM monitoring, and
  Real time alerts for follow-up of high E ν events.

- Combined ν & EM observations will enable us to
  - Identify the CR (UHE & G-CR) sources,
  - Resolve open "cosmic-accelerator" physics Qs
    (related to BH-jet systems, particle acc., rad. mechanisms),
  - Constrain ν physics, LI, WEP.